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FINAL REPORT

#F44620-73-C-0003

NONLINEAR HEATING OF PLASMAS

BY HIGH POWER LASERS

August 1972 - July 1976

Martin V. Goldman

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This report covers research on "Nonlinear Heating of Plasmas by High Power Lasers", ~~supported by Air Force Office of Scientific Research Contract #F44620-73-C-0003, for the period August 1972 through July 1976 (final report).~~ The overall objective of the program was to study the interaction of intense laser radiation with a high density plasma, such as that produced by radiation impinging on a cold target or from a pre-existing plasma.

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I. Introduction

From August 1972 to July 1976 we have performed extensive research on "Nonlinear Heating of Plasmas by High Power Lasers," supported by Air Force Office of Scientific Research Contract #F44620-73-C-0003. The AFOSR affiliation was preceded in 1972 by research on nonlinear laser heating under contract with the Air Force Weapons Laboratory, Kirtland Air Force Base.

The overall objective of the program was to study the interaction of intense laser radiation with a high density plasma, such as that produced by radiation impinging on a cold target or from a pre-existing plasma. The scientific accomplishments are contained in ten papers published or accepted for publication in leading refereed journals, four additional publications submitted or in progress, two completed Ph.D. theses, and numerous internal reports, and invited and contributed papers. Valuable collaborations were established with scientists at Kirtland Air Force Base, the Air Force Academy at Colorado Springs, Los Alamos Scientific Laboratories, and Culham Laboratories in England. We believe our research has significantly advanced fundamental theoretical and experimental understanding of the interaction of intense radiation with plasmas.

II. Past Accomplishments and Collaborations under AFOSR Contract #F44620-73-C-0003

Our accomplishments under Air Force sponsorship can best be described within the categories of publications, presentations, collaborations, and other research. Below we list items under these categories, with a brief description of the significance of the research.

A. Publications, Presentations, and other Research Results

1. *"Nonlinear Saturation of Parametric Instability,"* D. F. DuBois and M. V. Goldman, Physics of Fluids 15, 919 (1972). This was the first theoretical calculation of the saturation level of Langmuir waves excited by the radiation-induced electron-ion decay instability. The calculation is important for laser-plasma heating and for ionospheric modification by high-power radar. It is a necessary prerequisite to any theory of anomalous absorption or transport. We also calculated the cross section for scattering by a second radiation beam.

2. *"Spectrum and Anomalous Resistivity for the Saturated Parametric Instability,"* D. F. DuBois and M. V. Goldman, Physical Review Letters 28, 218 (1972). This letter extended the work of the previous paper and gave an analytical theory of the three-dimensional saturated Langmuir

wave spectrum. Of even more importance, we calculated the anomalous high-frequency resistivity of a plasma in an intense radiation field due to the equal-temperature parametric decay instability.

3. *"Nonlinear Wave Optics of Parametric Pump Radiation in an Inhomogeneous Plasma,"* D. F. DuBois, M. V. Goldman, and D. McKinnis, Physics of Fluids 16, 2257 (1973). Using the anomalous resistivity found in the previous work, we numerically solved the nonlinear wave equations for laser radiation propagating into an inhomogeneous, overdense plasma. Strong anomalous absorption was found for sufficiently intense radiation.

4. *"Stimulated Diffusion Scattering in Ionospheric Modification,"* R. L. Berger, M. V. Goldman, and D. F. DuBois, Physics of Fluids 18, 207 (1975). A new radiation-induced instability was found with demonstrated importance for ionospheric modification and possible implications for laser-plasma interaction as well. The instability is related to stimulated Brillouin scattering, but with a "diffusion mode" replacing the ion-acoustic wave.

5. *"Parametric Instabilities in Finite Inhomogeneous Media,"* D. F. DuBois, D. W. Forslund, and E. A. Williams, Physical Review Letters 33, 1013 (1974). Effects of finite size and inhomogeneity were taken into account here in the general linear theory of parametric instabilities excited

by radiation. Thresholds for absolute and convective instabilities were found in this very general theory.

6. *"Upper-Hybrid Solitons and Oscillating Two-Stream Instabilities,"* M. Porkolab and M. V. Goldman, Physics of Fluids 19, 872 (1976). The nonlinear evolution of purely growing instabilities in a magnetic plasma was studied. Soliton solutions were found. One potential application is to laser heating of a magnetically confined plasma, such as a dense plasma focus device.

7. *"Three-Dimensional Langmuir Wave Instabilities in Type III Radio Bursts,"* S. Bardwell and M. V. Goldman, Astrophysical Journal, November 1976 issue (in press). The three-dimensional parametric instabilities excited by the unstable waves driven by an electron beam were studied here. Under certain conditions it was found that Langmuir wave energy could migrate into directions oblique to the beam. A new instability, called the stimulated modulational instability, was found. Also, the oscillating two-stream instability was found to have the properties of a filamentational instability under certain conditions. L. Thode of Los Alamos has suggested that such effects may be important for laboratory relativistic electron beams, as well.

8. *"Space-Time Formulation of Weak Plasma Turbulence Theory,"* D. F. DuBois (accepted for publication in the 1976 volume of Physics of Fluids). Elements of a general theory

of weak plasma turbulence were set forth in this paper. Virtues of this formulation are its generality, and that it is in the space-time domain rather than in Fourier-space.

9. *"Nonlinear Theory of Parametric Instabilities in Plasma,"* D. F. DuBois and B. Bezzerides (accepted for publication in the 1976 volume of Physics of Fluids). A saturation theory is derived for the $2\omega_p$ instability and the electron-ion decay instability at unequal temperatures. Unlike the earlier saturation theories which relied on induced-scattering off-ions, this model relies on reduction of the effective wave-wave interaction matrix-element due to mode-coupling with the entire Langmuir spectrum.

10. *"On the Damped Nonlinear Schroedinger Equation,"* D. Nicholson and M. V. Goldman, Physics of Fluids, September 1976 issue (in press). A nonlinear Schroedinger equation is known to govern the evolution of the oscillating two-stream instability excited by radiation. In this paper both Landau damping and collisional damping were examined as perturbation to the undriven soliton solutions of the nonlinear Schroedinger equation. Soliton distortions as well as velocity changes were studied.

11. *"Langmuir Envelope Shocks with Landau Damping,"* M. V. Goldman and D. Nicholson, in preparation for submission to Physics of Fluids (preliminary manuscript included as an attachment to this report). Here, we have investigated

steady-state solutions to the Landau-damped nonlinear Schroedinger equations that are to be distinguished from the time-dependent solutions studied in (10). Langmuir envelope shocks are found, rather than solitons. For an infinite plasma, the frequency determines amplitude and (subsonic) speed. In a semi-infinite plasma, the shock is stationary, its frequency determines its amplitude, and the energy flux through the boundary determines the spatial extent of the field. The significance of this new work is that, under certain conditions, intense laser fields may drive high-frequency envelope shocks, rather than solitons.

12. "*CO_2-Excited Langmuir Turbulence in a Dense Plasma Focus*," M. J. Forrest, P. D. Morgan, N. J. Peacock, K. Kuriki, Euratom-UKAEA Association for Fusion Research, Culham Laboratories, Abingdon, Oxon, England; and M. V. Goldman and T. Rudolph, Department of Astro-Geophysics, University of Colorado. Submitted June 1976 to Physical Review Letters (copy is included as an attachment to this report). (Invited talk on this subject was given by M. V. Goldman, May 1976 at the Anomalous Absorption Conference at Vancouver, B.C.) This work represents the fruits of a three year collaborative effort with Dr. Peacock's experimental group in Culham (see collaborations). CO_2-Excited Langmuir turbulence has been detected by forward ruby-laser scattering in a dense plasma focus device. We have constructed a new theory based on the convectively-saturated electron-

ion parametric-decay instability. The theory gives excellent agreement with experimentally-determined ruby-scattering cross section as a function of CO_2 intensity. The experiment provides the first real evidence for this instability and turbulence in a laser-driven high-density plasma.

13. *"Linear Inhomogeneous Theory of CO_2-Enhanced Langmuir Turbulence,"* M. V. Goldman. (Second memorandum to Peacock at Culham Laboratories; included as an attachment to this report.) This will form the basis for a paper to be submitted to Physics of Fluids. This paper contains the theoretical details relevant to the Peacock experiment. A WKB theory in slab geometry predicts a linear convective saturation of the electron-ion decay instability in an inhomogeneous plasma with equal electron and ion temperatures. New effects included in this analytic theory are ion-discreteness, first-order WKB swelling in the laser and Langmuir fields, and beat-spontaneous-emission (in which low-frequency Cerenkov emission beats against the laser field and is thereby frequency upshifted to act as a source for Langmuir waves).

14. *"Nonlinear Equilibration of Electrons and Ions,"* D. McKinnis and M. V. Goldman, Appendix A of the 74-75 Interim Report, this contract. For a laser field sufficiently intense that the driven and thermal electron velocities are comparable, a nonlinear oscillating particle-orbit phenomenon occurs which tends to reduce the effective electron-ion

binary-encounter collision frequency. Under these conditions the high-frequency conductivity is reduced, and the effect is called multiphoton absorption. In this paper we have calculated the multiphoton effect on the electron-ion equilibration frequency and found it can be drastically reduced.

15. *"Transport Processes within a Plasma Driven by a High-Frequency Electric Field,"* D. McKinnis, Ph.D. Thesis, University of Colorado, June 1976 (attachment to this report). The material covered in this doctoral dissertation includes the effect described in (14) above. However, it also includes a calculation of the nonlinear electron thermal conductivity in an intense radiation field. An anomalous thermal conductivity has been found, which is increased, relative to equilibrium, by multiphoton effects. In the strong-field limit, an analytical asymptotic form of the conductivity is derived. Only contributions from electron-electron encounters remain in this limit. It should be possible to reach this nonlinear domain in the early stages of laser-target or laser-plasma-focus-device interactions.

16. *"Pump Wavenumber Dependent Effects in the Parametric Instabilities of a Plasma,"* S. Bardwell, Ph.D. Thesis, University of Colorado, June 1976 (attachment to this report). This Ph.D. dissertation consists of two parts: First, it treats the effects of a standing wave pump on parametric instabilities. Of more importance is the second

part, which deals with three-dimensional parametric instabilities driven by a finite wavenumber Langmuir wave (whose origin may be caused by an electron beam) in a plasma with equal electron and ion temperatures. The work is related to item (7), above, but includes other applications besides type III solar radio bursts; among these are auroral arcs and laboratory beams.

17. *Invited and Contributed Talks*

"Spectrum and Anomalous Resistivity for the Saturated Parametric Instability," M. V. Goldman, invited talk, University of Rochester (for M. J. Lubin), January 1972.

"Anomalous Absorption and Parametric Instabilities," D. F. DuBois; "Time-Dependent Evolution of Parametric Instability Toward Saturation," B. Godfrey, M. V. Goldman, and D. F. DuBois; "Nonlinear Wave Optics of Absorption in an Inhomogeneous Plasma," D. F. DuBois and M. V. Goldman: Papers presented at the Symposium on Anomalous Absorption of Intense Radiation, March 1972, University of Colorado, Boulder, Colorado.

"Parametric Instability and Anomalous Transport," M. V. Goldman, invited talk given at the American Physical Society Plasma Physics Division Meeting, June 1972, Albuquerque, New Mexico.

"Nonlinear Theory of Parametric Decay Instability for $T_e >> T_i$," D. F. DuBois and M. V. Goldman, paper presented

at the 1972 Annual Meeting of the Plasma Physics Division, American Physical Society, Novmeber 1972, Monterey, California.

"Parametric Instabilities of Diffusion Modes across a Magnetic Field," M. V. Goldman and D. F. DuBois, paper presented at the Anomalous Absorption Conference, March 1973, Los Alamos, New Mexico.

"Stimulated Back-Scattering from Diffusion Modes with $\underline{k} \perp \underline{B}_o$," M. V. Goldman and D. F. DuBois; "Linear and Nonlinear Theory of Parametric Instabilities in Plasmas," D. F. DuBois: papers presented at the International Congress on Waves and Instabilities in Plasmas, Innsbruck, Austria, April 1973.

"Stimulated Back-Scattering from Diffusion Modes with $\underline{k} \perp \underline{B}_o$," M. V. Goldman, lecture presented at the Centre de Recherches en Physique des Plasmas, Lausanne, Switzerland, May 1973.

"Saturation and Anomalous Resistivity for the $2\omega_p$ Parametric Decay instability," D. F. DuBois, M. V. Goldman, and S. Bardwell; "Effects of Viscosity and Thermal Fluctuations on Diffusion Modes and Stimulated Diffusion Scattering," R. Berger, M. V. Goldman, and D. F. DuBois: Papers presented at the Annual APS Plasma Physics Division Meeting, Philadelphia, Pennsylvania, November 1973.

"Remarks Concerning Multiphoton Inverse Bremsstrahlung," D. McKinnis and M. V. Goldman; "A New Parametric Instability

of the Oscillating Two-Stream Variety," S. Bardwell and M. V. Goldman; "Stimulated Diffusion Scattering," R. L. Berger, M. V. Goldman, and D. F. DuBois: Papers presented at the Fourth Annual Anomalous Absorption Conference, Livermore, California, April 1974.

"Nonlinear Waves and Fluctuations in Plasmas," M. V. Goldman, invited lectures at the Centre de Recherche en Physique de Plasmas, Ecole Polytechnique Federale de Lausanne, Switzerland, July 1974.

"Standing-Wave Pumped Parametric Instabilities," S. Bardwell and M. V. Goldman, 16th Annual American Physical Society Plasma Physics Division Meeting, Albuquerque, New Mexico, October 1974.

"Soliton Formation and Upper-Hybrid Waves," M. Porkolab and M. V. Goldman, Fifth Anomalous Absorption Conference, Los Angeles, California, April 1975.

"Laser Excited Langmuir Solitons," M. V. Goldman, invited lecture at Bell Laboratories, New Jersey, January 1975.

"Laser Fusion and Langmuir Solitons," M. V. Goldman, invited talk at the University of Southern California, April 1975.

"Cyclotron Heating by the Electron-Ion Decay Instability," M. V. Goldman, Anomalous Absorption Symposium, Los Angeles, April 1975.

"Upper-Hybrid Solitons and Oscillating Two-Stream Instabilities," M. V. Goldman; "Oscillating Two-Stream and Stimulated Modulational Processes in the Saturation of Warm Electron Beam Instabilities," S. Bardwell and M. V. Goldman: Papers presented at the American Physical Society Meeting, St. Petersberg, Florida, October 1975.

"3-D Stabilization of Electron Streams in Type III Solar Radio Bursts," S. Bardwell and M. V. Goldman, paper presented at the American Geophysical Union Meeting, San Francisco, California, December 1975.

"CO_2-Excited Langmuir Turbulence in a Dense Plasma Focus Device," Martin V. Goldman, invited 30-minute talk, 6th Annual Symposium on the Anomalous Absorption of Intense High Frequency Waves, Vancouver, May 11, 1976.

"On the Damped Nonlinear Schroedinger Equation," D. R. Nicholson and M. V. Goldman; "Theory of Multiphoton Transport," D. McKinnis and M. V. Goldman, contributed papers, presented at the 6th Annual Sumposium on the Anomalous Absorption of Intense High Frequency Waves, Vancouver, May 11, 1976.

"Solitons in Plasma Physics," M. V. Goldman and D. Nicholson, Aspen Center for Physics, July 1976.

"CO_2-Excited Langmuir Turbulence in a Dense Plasma Focus," N. J. Peacock, M. J. Forrest, P. D. Morgan, K. Kuriki,

M. V. Goldman, and T. Rudolph, Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berctesgaden, FRG, 6-13 October 1976.

18. *Symposium on Anomalous Absorption of Intense Radiation*, sponsored by the Air Force Weapons Laboratory, at the University of Colorado, Boulder, March 1972; M. V. Goldman, Chairman.

B. Collaborations and Interactions

1. *Major N. Roderick, AFWL:* Major Roderick collaborated with us while at the Air Force Academy by performing numerical calculations with our nonlinear wave-propagation code using density profiles more general than the linear profile employed in our paper (item A.3, above). He found that the nonlinear ponderomotive force caused a ripple to intensify. This work was presented by him in a paper at the American Physical Society meeting in Albuquerque, New Mexico, in 1974. He is presently engaged in numerical analysis of the radiation-driven nonlinear-Schroedinger equation. The object is to study the nonlinear evolution of the oscillating-two-stream instability, including fluctuations and damping. This program was outlined to him in the memorandum entitled, "Sequence of Numerical Problems Using Nonlinear Schroedinger Equation Code,"

contained in our Annual 1975 interim Report for this contract.

2. *Dr. N. Peacock, Culham Laboratories, England:* In May 1973 we approached Dr. Nicol Peacock of Culham Laboratories, England with a proposal for an experiment on the dense plasma focus-device which would enable a direct verification of our parametric instability theory predictions in a laser-heated high density plasma ($\sim 10^{19}$ particles per cm^3). A high-power CO_2 laser would drive the instabilities, and a ruby laser would be employed as an incoherent-scatter diagnostic of the unstable waves. This experiment has now been undertaken and is being funded by Culham at no direct cost to AFOSR. Positive results have now been obtained. Langmuir wave enhancement to a level 500 times above thermal equilibrium has been observed at a focused CO_2 intensity of 10^{10} W cm^{-2}. (See item 12 under publications, above.) Theoretical-experimental collaboration is still vigorously underway.

3. *Dr. D. F. DuBois, Los Alamos Scientific Laboratories:* A long history of successful theoretical collaboration with Dr. D. F. DuBois has been maintained while he was at Hughes Research Laboratories (prior to 1972), at the University of Colorado (1972-1972), and at Los Alamos Scientific Laboratories, where he is presently a senior research physicist. Scientific milestones, such as the first prediction of the radiation-induced parametric instability,

and the first saturation theory of that instability have come out of this collaboration. At present, we are working together on an important but difficult research problem in the nonlinear statistical theory of plasma instabilities: the issue is when can a coherent plasma collective-mode evolve out of a random-phase equilibrium, essentially as a phase-transition (see August 1, 1972 renewal proposal of this contract for details).

4. *Other Interactions:* Numerous useful interactions with scientists in the laser and plasma physics community have been maintained over the duration of AFOSR support. In 1972, we gave an invited lecture at the University of Rochester to Dr. M. Lubin's group, which had been using the results of our AFWL technical report #TR-72-101, "Nonlinear Laser Heating of a Plasma," in their numerical work. In addition (see above list of lectures presented) we have maintained contact with groups at Bell Laboratories, and with the quantum electronics community through Dr. R. Hellwarth of the University of Southern California. In the summer of 1975, D. N. Rostoker of the University of California at Irvine was a consultant here and brought us up to date on relativistic electron beams and ion acceleration. We maintain close ties with scientists at the Air Force Academy at Colorado Springs, and at Los Alamos Scientific Laboratories, with frequent mutual visits.